

Probing High Redshift Radiation Fields with Gamma-Ray Absorption

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ABSTRACT

The next generation of gamma-ray telescopes may be able to observe gamma-ray blazars at high redshift, possibly out to the epoch of reionization. The spectrum of such sources should exhibit an absorption edge due to pair-production against UV photons along the line of sight. One expects a sharp drop in the number density of UV photons at the Lyman edge ϵ_L . This implies that the universe becomes transparent after gamma-ray photons redshift below $E \sim (m_e c^2)^2 / \epsilon_L \sim 18 \text{ GeV}$. Thus, there is only a limited redshift interval over which GeV photons can pair produce. This implies that any observed absorption will probe radiation fields in the very early universe, regardless of the subsequent star formation history of the universe. Furthermore, measurements of differential absorption between blazars at different redshifts can cleanly isolate the opacity due to UV emissivity at high redshift. An observable absorption edge should be present for most reasonable radiation fields with sufficient energy to reionize the universe. Ly α photons may provide an important component of the pair-production opacity. Observations of a number of blazars at different redshifts will thus allow us to probe the rise in comoving UV emissivity with time.

1. Introduction

Our knowledge of UV radiation fields and energy injection into the IGM at $z > 5$ is fairly tenuous. There are two main constraints: observations of the integrated background light (Madan & Pozzetti 2000, Bernstein et al 1999), and the fact that no Gunn-Peterson trough is observed in the spectra of the highest-redshift quasar to date (Fan et al 2000), implying that the universe must be reionized by $z = 5.8$. The upcoming Next Generation Space Telescope (NGST) will be able to image high-redshift star clusters or AGNs in rest frame UV continuum emission (Haiman & Loeb 1997, 1998), and their redshifts may be obtained via H α observations (Oh 1999). Nonetheless, the redshift-binned number counts will be fairly sparse, and one is unlikely to probe sufficiently far down the luminosity function to get a good measure of the comoving emissivity as a function of redshift.

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Observations of gamma-ray blazars (“grazars”) probe extragalactic IR and UV radiation fields, by observing the pair production opacity to γ rays at the high energy end (Gould & Schreder 1967, Stecker, De Jager & Salamon 1992, Madau & Phinney 1996, Primack et al 1999). All theoretical models have confined their predictions to low redshift grazars, with the exception of Salamon & Stecker (1998), who computed the γ -ray opacity up to $z=3$. They concluded that because the stellar emissivity peaks between $z=1$ and $z=2$, the γ -ray opacity shows little increase at high redshift, and thus is not dependent on the initial epoch of galaxy formation.

To date, EGRET has detected 66 gamma-ray loud blazars (Hartman et al 1999), out to redshifts $z > 2$. The next generation of gamma-ray telescopes (GLAST, CELESTE, STACEE, MAGIC, HESS, VERITAS, and Milagro) should greatly enlarge this sample. If the low redshift correlation between black hole mass and bulge mass (Magorrian et al 1998) continues to high redshift, then it is possible that high-redshift halos could host mini-quasars (Haiman & Loeb 1998, Haehnelt, Natarajan & Rees 1998), which should be detectable in rest frame UV emission by NGST and X-ray emission by Chandra (Haiman & Loeb 1998, 1999) in the redshift range $z \sim 5 - 15$. This raises the exciting possibility that grazars could be detected at similarly high redshifts. It is worth noting that EGRET has detected ~ 56 sources at high Galactic latitudes $b > 10^\circ$ (Mukherjee, Grenier & Thompson 1997), with no known counterparts at other wavelengths. Their spatial distribution and log N- log S plot can be well fit by a Galactic component plus an isotropic, extragalactic contribution. Some of these may well be unidentified high-redshift blazars.

In this paper, I point out that if grazars are detected at high redshifts $z > 3$, the pair production opacity to gamma ray photons can be used to probe the comoving emissivity longward of the Lyman break at these extremely high redshifts, independent of the star formation rate at lower redshifts. Due to the small escape fraction of ionizing photons $f_{esc} < 5\%$ from host galaxies, as well as the high photoelectric opacity of the IGM at these wavelengths, the comoving number density of UV photons exhibits a sharp drop at the Lyman edge at all redshifts. Thus, there is only a limited pathlength over which a gamma-ray photon can pair produce against UV photons, before it redshifts to energies which require UV photons above the Lyman edge for pair production to take place. For $z < z_{break}$, the universe becomes optically thin to the gamma-ray photon. Thus, the detection of an absorption edge in a high-redshift grazar places an immediate constraint on the mean radiation field over the redshifts $z_{break} < z < z_s$. Furthermore, measurement of the different absorption at a given observed energy between blazars at redshifts z_1, z_2 places an immediate constraint on the radiation field in the redshift range $z_1 < z < z_2$. Detection of grazars at a number of redshifts would then enable one to probe the UV emissivity history of the universe.

In all numerical estimates, we assume a background cosmology given by the ‘concordance’ values of Ostriker & Steinhardt (1995): $(\Omega_m, \Omega_\Lambda, \Omega_b, h, \sigma_{8h^{-1}}, n) = (0.35, 0.65, 0.04, 0.65, 0.87, 0.96)$.

2. Gamma-Ray Blazars

A detailed study of the detectability of high-redshift blazars is beyond the scope of this paper. In this section, I merely show that it is plausible that GLAST will be able to detect high redshift blazars.

With a point source sensitivity of $S(E > 100\text{MeV}) \sim 2 \times 10^{-7} \text{photons s}^{-1}\text{cm}^{-2}$, EGRET has detected ~ 66 high-redshift blazars out to $z > 2$ (Hartman et al 1999). The associated gamma-ray luminosities correspond to $L_\gamma = 10^{46} - 10^{49} \text{erg s}^{-1}$, and typically dominate the bolometric luminosity of the AGN, with $L_\gamma/L_B \sim 1 - 1000$. The upcoming gamma-ray telescope GLAST (see <http://glast.gsfc.nasa.gov>) will be 2 orders of magnitude more sensitive, with a detection threshold of $S(E > 100\text{MeV}) \approx 2 \times 10^{-9} \text{photons s}^{-1}\text{cm}^{-2}$ for a 5σ detection with a 50 hour integration, and $S(E > 1\text{GeV}) \approx 10^{-10} \text{photons s}^{-1}\text{cm}^{-2}$ (these thresholds correspond to the same detection limit for a $L_\nu \propto \nu^{-\alpha}$ source spectrum where $\alpha = 1$). Goals for GLAST include a broad energy coverage from $10\text{ MeV} - > 300\text{ GeV}$, with a spectral resolution of $\sim 2\%$ in the $> 10\text{ GeV}$ range, a field of view of $> 3\text{ sr}$, and a source location determination accuracy of $30\text{ arcsec} - 5\text{ arcmin}$. During its lifetime, it will perform an all-sky survey similar to that conducted by EGRET. Sources of the same or somewhat fainter luminosity as those detected by EGRET may be seen by GLAST out to extremely high redshifts, $z \sim 10$.

Will such luminous sources will be present at high redshift? If the AGN is assumed to emit all its energy at gamma-ray wavelengths at the Eddington luminosity, the inferred black hole mass is extremely high, $M_{bh} = 10^{10} M_\odot (L_{edd}/10^{48} \text{erg s}^{-1})$. However, there are two reasons why gamma ray sources of high apparent luminosity do not require such massive black holes: (i) even if all photons are radiated isotropically, if most of the radiation emerges at high energies (as appears to be the case in gamma-ray blazars), then Klein-Nishina effects must be taken into account (Dermer & Gehrels 1995). The inferred black hole mass, given by $M_8^{KN} \geq \frac{3\pi d_L^2 (m_e c^2)}{2.126 \times 10^{46} \text{erg s}^{-1}} \frac{F(\epsilon_l, \epsilon_u)}{(1+z)} \ln[2\epsilon_l(1+z)]$ (where $F(\epsilon_l, \epsilon_u)$ is the observed flux between the lower and upper bandpass limits ϵ_l, ϵ_u) typically drops by 3 orders of magnitude, so a $10^{48} \text{erg s}^{-1}$ source only requires a $10^7 M_\odot$ black hole. (ii) There is strong evidence for relativistic beaming in blazars (e.g., through the observation of superluminal jets (von Montigny et al 1995)). In fact, if blazars were not beamed, we would not be able to see any gamma-rays from them due to the high pair production opacity at the source; beaming reduces the luminosity/radius ratio by a factor δ^{p+1} , allowing photons to escape (Maraschi et al 1992). Here, if α is the spectral index of the source, then $p = 3 + \alpha$ for a moving sphere in the Synchrotron Self-Compton (SSC) model, while $p = 4 + 2\alpha$ in the External Radiation Compton (ERC) model; $\delta = [\gamma(1 - \beta \cos \theta)]^{-1}$ is the relativistic Doppler factor, and γ is the Lorentz factor. If \mathcal{L} is the initial intrinsic luminosity of the jet in gamma-ray emission, beaming boosts the observed luminosity of the jet to $L = \delta^p \mathcal{L}$. For $\theta \sim 0^\circ$, then $\delta \sim 2\gamma$, and the observed luminosity is amplified by a factor of thousands. The strong relativistic beaming reduces the fraction of sources which are visible, since they can only be seen when viewed along the jet axis. For instance, for $\gamma = 6$, and $\alpha = 1$, in the SSC model the observed luminosity is reduced by an order of magnitude from its maximum if the jet is pointing 8.5° from our line of sight, and two orders of magnitude if the jet is pointing 14.2° from

our line of sight. Note that the black hole masses derived for a number of low redshift blazars from variability timescale and transparency arguments lie in the range $10^7 - 10^8 M_\odot$ (Cheng et al 1999, Hartman et al 1996, Becker & Kafatos 1995, Romero et al 2000). The luminosity of these blazars is so high they could be seen at high redshift with GLAST, and black hole masses of $10^7 - 10^8 M_\odot$ are reasonably abundant at high redshift in certain models of AGN formation (Haiman & Loeb 1998). Note that for a set of blazars of constant intrinsic luminosity \mathcal{L} and comoving number density, the redshift distribution of detected sources in a flux-limited survey flattens considerably and extends to higher redshifts as the Lorentz factor increases (Dermer & Gehrels 1995).

At present, the modelling of even the low-redshift population of gamma-ray blazars is a matter of considerable debate. Models which attempt to account for the unresolved gamma ray background with faint blazars either extrapolate the observed γ -ray luminosity function obtained with EGRET (Chiang & Mukherjee 1998) or use an assumed conversion between the observed radio loud AGN luminosity function and the blazar luminosity function (Stecker & Salamon 1996). In this paper, I use a highly simplified model to estimate the detectability of high-redshift blazars. I assume that the intrinsic luminosity \mathcal{L} of the jet in gamma-ray emission (prior to beaming) scales with the luminosity of the accretion disk $\mathcal{L} = fL_{disk}^\beta$, where the optical B-band luminosity is taken to be an accurate reflection of L_{disk} (in particular, assuming the median quasar spectrum of Elvis et al (1994), a $1 M_\odot$ black hole shining at the Eddington luminosity has a B-band luminosity of $5.7 \times 10^3 L_{B,\odot}$). Such a jet-disk correlation is observed in the ratio of observed radio (i.e., after beaming) to optical luminosities (Falcke, Malkan & Biermann 1995). I also assume relativistic beaming with $L = \delta^p \mathcal{L}$, where $p = 3 + \alpha$ (and $\alpha = 1$, the average spectral index observed in the EGRET blazars). The change in the observed luminosity function due to the effects of relativistic beaming is given by (Urry & Padovani 1995):

$$\Phi_{obs} = \int d\mathcal{L} P(L|\mathcal{L}) \Phi_{intr}(\mathcal{L}) \quad (1)$$

where the probability of observing luminosity L given the intrinsic luminosity \mathcal{L} is given by:

$$P(L|\mathcal{L}) = P(\delta) \frac{d\delta}{dL} = \frac{1}{\beta \gamma \delta} \mathcal{L}^{1/p} L^{-(p+1)/p} \quad (2)$$

I use the fit to the observed B-band luminosity function $\phi(L_B, z)$ from Pei (1995). I adjust the relation $\mathcal{L} = fL_{disk}^\beta$ and the Lorentz factor γ (note that since the distribution of blazar Lorentz factors is unknown, I assume they all have the same Lorentz factor) to fit the number of blazars detected by EGRET and their redshift distribution. I ignore the effects of blazar flaring, which increases the luminosity by some factor A (where typically $A \sim 5$) some fraction ξ of the time (where typically $\xi \sim 0.03$), which results in a second term $\xi \phi(L/A)$, since these two degrees of freedom, the normalization (chosen by selecting γ and thus the beaming angle) and luminosity boost (chosen by the combination $L = \delta^p fL_{disk}^\beta$), are already present in our model. I find that $\mathcal{L}_{13} = 3.2 \times 10^{-2} L_{B,13}^{0.9}$ (where $L_{13} = (L/10^{13} L_\odot)$ and $\gamma = 6$ provides a good fit (see Fig 1, top panel). Note that since $L_{\gamma,13} < (2\gamma)^p L_{B,13}^{0.9} \sim 600 L_{B,13}^{0.9}$ (corresponding to $\theta = 0$), these relations result in a SED which is in reasonable agreement with the observed SEDs of gamma-ray blazars

(see Fig 1 in Ghisellini et al 1998), where $L_\gamma/L_B \sim 10 - 100$ typically, although it can range from 1 – 1000. Furthermore, the Lorentz factor $\gamma \sim 6$ is in reasonable agreement with the relativistic Doppler factor $\delta < 2\gamma$ from models which take into account the SED, time variability, and gamma-ray transparency of blazars; the derived $\delta \sim 10 - 20$ (Ghisellini et al 1998). The somewhat lower Doppler factors I have adopted conservatively underestimate the number of high-redshift blazars.

I then extrapolate this model to high redshift by applying it to the Press-Schechter based model of Haiman & Loeb (1998) for quasars. In this model, which is calibrated to the observed luminosity function of Pei (1995) at lower redshifts, each halo with $T_{vir} > 10^4$ K hosts a black hole with mass $M_{bh} = 10^{-3.2} M_{halo}$ which shines at the Eddington luminosity for $t_o \sim 10^6$ years. The result is shown in the bottom panel of Fig 1, which shows that gamma-ray blazars may be detected out to $z \sim 7$. By the time GLAST is launched, a large database of quasars with known redshifts will be available (e.g. from the SLOAN digital sky survey, SDSS (York et al 2000)), and many high-redshift blazars can be selected simply by identifying their optical counterparts. I emphasize once again that this highly simplified model is only intended to serve as a plausibility argument. The main point is that while the Press-Schechter formalism predicts that massive halos $M_{halo} > 10^{11} M_\odot$ expected to host supermassive black holes of the requisite luminosity become exponentially rare at high redshift, processes which increase the luminosity of a lower luminosity population (beaming $L = \delta^p \mathcal{L}$, flaring $L = AL$) create a power-law tail of bright sources. I have neglected a tail to the distribution of Lorentz factors, or flaring, which could further flatten the redshift distribution of detectable sources, increasing the maximum redshift out to which sources can be seen. Finally, gravitational lensing could bring otherwise undetectable sources into view, although the low optical depths for strong lensing (e.g. $\tau \approx 6 \times 10^{-3}$ for $z_s = 7$, Porciani & Madau 2000) imply that this should only have a small impact on number counts.

3. Calculating pair production opacity

The pair-production optical depth for a photon observed at energy E_o and emitted from a source at redshift z_s is given by (e.g., Madau & Phinney 1996):

$$\tau(E_o, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_{-1}^1 d(\cos\theta) (1 - \cos\theta) \int_{\epsilon_{th}}^\infty d\epsilon n(\epsilon, z) \sigma(E, \epsilon, \theta) \quad (3)$$

where $E = (1 + z)E_o$, and ϵ_{th} is given by the criterion that pair production can take place, which requires that $E\epsilon(1 - \cos\theta) \geq 2(m_e c^2)^2$. For a given energy E , the pair production cross-section $\sigma(E, \epsilon, \theta)$ rises sharply from the threshold energy ϵ_{th} , reaches a peak of $0.26\sigma_T$ at $\epsilon = 2\epsilon_{th}$, and finally falls off as ϵ^{-1} for $\epsilon \gg \epsilon_{th}$. To calculate the optical depth of the universe to gamma-ray photons emitted at high redshift, we need to know the number density of photons as a function of energy and redshift. Before doing so in detail, I make some simple estimates.

One can perform a simple order of magnitude estimate to show that the minimal comoving emissivity required to reionize the universe implies a high pair-production opacity for $E > E_{th}$, but

a low opacity for $E < E_{th}$, where we define the threshold energy in the rest frame of the source for pair production against UV photons at the Lyman edge as $E_{th} \sim (m_e c^2)^2 / \epsilon_L \approx 18 \text{ GeV}$. This is because the number density of UV photons plummets at wavelengths shortward of the Lyman limit; the pair production opacity is thus dominated by soft photons $\epsilon < \epsilon_L = 13.6 \text{ eV}$. For the universe to be reionized, a minimum of 1 ionizing photon per baryon must be emitted. Thus, the comoving number density of ionizing photons is $n_\gamma(E > E_L) > n_b(1 + n_{rec}) \sim 10^{-7}(1 + n_{rec}) \text{ cm}^{-3}$, where $(1 + n_{rec})$ is the average number of times each baryon recombines during the reionization epoch. The pair production cross section peaks when $E\epsilon \sim (m_e c^2)^2$, with a value of $\sigma_{pp} \sim 0.26 \sigma_T$. Thus, across a Hubble volume, the optical depth for photons with $E < E_{th}$ is $\tau \sim n_{\gamma,proper}(E > E_L) \sigma_{pp} l_H \sim 5 \times 10^{-3}(1+z/10)^{1.5}(1+n_{rec})$, which is undetectably small. What is the pair production opacity for photons with $E > E_{th}$? We can scale the number density of photons longward of the Lyman limit with respect to the number of ionizing photons produced. There are 3 factors involved: (i) f_{esc} . Observations of our own Galaxy (Dove, Shull, & Ferrara 2000, Bland-Hawthorn & Maloney 1999) and local starbursts (Leitherer et al 1995) find the escape fraction of ionizing photons from galaxies into the IGM is of order $f_{esc} \sim 3 - 6\%$, and radiative transfer calculations find that the escape fraction should decrease strongly with redshift (Woods & Loeb 1999, Ricotti & Shull 2000). The actual comoving number density of ionizing photons produced in starbursts is $f_{esc}^{-1} n_b(1 + n_{rec})$, where $f_{esc} \sim 5\%$ is the escape fraction of ionizing photons from the halo. (ii) f_{break} . Photoelectric absorption in stellar atmospheres produces a sharp drop in the flux at the Lyman edge. For a Salpeter IMF with metallicity $\sim 10^{-2} Z_\odot$, there are $f_{break} \sim 5$ times as many photons emitted longward of the Lyman limit as there are shortward of it, integrated over the history of the starburst. (iii) $f_{opacity}$, due to intergalactic absorption. The energy density $U_\gamma \sim \frac{4\pi}{c} J_\nu$ where $J_\nu \sim \epsilon_\nu \lambda_{mfp}$ where λ_{mfp} is the mean free path of a photon of frequency ν . While the universe is optically thin to photons longward of the Lyman limit, it is optically thick to ionizing photons, which have a much shorter mean free path. The energy density of ionizing photons is lower by a factor $f_{opacity} = \frac{\langle \lambda_{mfp}(E < E_L) \rangle}{\langle \lambda_{mfp}(E > E_L) \rangle} > 10$ due to their high absorption rate. The mean free path of ionizing photons decreases strongly with redshift and for $z > 2$ the radiation field is largely local, due to the large increase in the number of adsorbers (e.g., Madau, Haardt & Rees 1999). Thus, we have $\frac{n_\gamma(E < E_L)}{n_\gamma(E > E_L)} \sim f_{esc}^{-1} f_{break} f_{opacity} \sim 10^3 \left(\frac{f_{esc}}{0.05} \right)^{-1} \left(\frac{f_{break}}{5} \right) \left(\frac{f_{opacity}}{10} \right)$. This implies that the pair production opacity longward of ϵ_L over a Hubble length is much greater, $\tau \sim 5(1+z/10)^{1.5}(1+n_{rec})$. A similar estimate may be obtained by normalizing to the observed metallicity of the IGM at $z \sim 3$, $Z \sim 10^{-2} Z_\odot$; this can be shown to correspond to ~ 10 ionizing photons per IGM baryon (Miralda-Escude & Rees 1997), or a comoving number density of $\sim 50 n_b$ for photons longward of the Lyman break, compared to the previous estimate of $\sim 100 \left(\frac{f_{esc}}{0.05} \right)^{-1} \left(\frac{f_{break}}{5} \right) n_b$.

The expectation of a sharp drop in the intensity of the ambient intergalactic radiation field at the Lyman edge is fairly robust. A recent composite spectrum of 29 Lyman break galaxies (LBGs) exhibit an observed flux ratio $L(1500)/L(900) = 4.6 \pm 1.0$, which is consistent with no internal photoelectric absorption, i.e. $f_{esc} \sim 1$ (Steidel, Pettini & Adelberger 2000). Note that the authors themselves stress this result should be treated as preliminary; the result could be due to a large

number of uncertainties or selection effects, among them the fact that these galaxies were selected from the bluest quartile of LBGs. Even so, if this is typical of all high redshift galaxies, the observed Lyman break (likely due to absorption by stellar atmospheres) and expected processing by intergalactic absorption at high redshift imply a Lyman edge $\frac{n_\gamma(E < E_L)}{n_\gamma(E > E_L)} > 50$. Similar considerations of internal and intergalactic photoelectric absorption apply if quasars dominate the ionizing radiation field.

As a photon redshifts, it has to interact with higher energy photons to pair produce. A photon is able to pair produce until it redshifts below E_{th} , i.e., the universe is optically thin to a photon once it redshifts below $(1+z_{th}) \sim \frac{E_{th}}{E_s}(1+z_s)$, where E_s is the original energy of the photon at source redshift z_s . Thus, there is a fairly well-defined pathlength $\delta l = \frac{c}{H_0}((1+z_s)^{-3/2} - (1+z_{th})^{-3/2})$ over which a photon may pair produce. This has the fortunate consequence that low redshift photons do not affect photons emitted near E_{th} ; thus, near the threshold energies one is always probing the average radiation field at redshifts comparable to the source redshift. The flux decrement at a given frequency measures the average number density of photons redward of the Lyman break over the associated redshift interval, $n_\gamma \sim \tau/(\Delta l \sigma_{pp})$. Gamma ray absorption measurements thus provide a fairly clean measurement of radiation fields at high redshift which are uncomplicated by radiative transfer effects since (apart from unimportant H_2 opacity effects) the universe is optically thin to photons redward of the Lyman limit. In particular, photons longward of the Lyman limit establish a homogeneous, isotropic radiation field early in the history of the universe. As the pathlengths for pair production opacity to become significant are typically of order a Hubble volume, opacity fluctuations due to Poisson fluctuations or source clustering are insignificant. The measured background radiation field may be compared directly against the expected background from measurements of the source luminosity function by direct imaging of high redshift sources in mid-IR with NGST, where fast photometric redshifts may be obtained using the Gunn-Peterson break. A comparison of the two should in principle allow one to check the completeness of a survey at NGST flux limits.

Let us now use a specific model of high-redshift star formation to calculate the abundance of UV photons at high redshift. The solution of the cosmological radiative transfer equation yields the mean specific intensity of the radiation background at the observed frequency ν_o , as seen by an observer at redshift z_o as (Peebles 1993):

$$J(\nu_o, z_o) = \frac{1}{4\pi} \int_{z_o}^{\infty} dz \frac{dl}{dz} \frac{(1+z_o)^3}{(1+z)^3} \epsilon(\nu, z) e^{-\tau_{\text{eff}}(\nu_o, z_o, z)} \quad (4)$$

where $\nu = \nu_o(1+z)/(1+z_o)$, and $\tau_{\text{eff}}(\nu_o, z_o, z)$ is the effective optical depth of the IGM to radiation emitted at z and observed at z_o at frequency ν_o . Redward of the Lyman edge, radiative transfer is particularly simple as the universe is optically thin, and only the redshifting of photons is important (there is one caveat to this statement: the optical depth of the IGM in the Lyman resonance lines prior to reionization is very large; thus whenever a photon redshifts into a $\text{Ly}\beta$ or higher order Lyman resonance, it is reprocessed into a $\text{Ly}\alpha$ and Balmer or lower order line photon (see Hauman, Rees & Loeb 1997)). However, this merely causes a modulation in the spectrum in the 11.2–13.6

eV range, redistributing photons to the Ly α and Balmer wavelengths. The large typical energy intervals of target photons (see Fig 3, top panel) implies that this redistribution causes the pair-production opacity to remain the same or increase. I therefore ignore this complication). The number density of photons in an energy interval is then given by $\frac{dn}{d\epsilon} = \frac{4\pi}{hc} J_\nu$. I model the star formation history $\dot{\Omega}_*$ of the high redshift universe with the semi-analytic models of Haiman & Loeb (1997), in which a fixed fraction $f_{star} \sim 1.7 - 17\%$ of the gas (normalised to reproduce the observed IGM metallicity at $z = 3$ of $Z = 10^{-3} - 10^{-2} Z_\odot$) in halos with $T_{vir} > 10^4 \text{K}$ (which are able to undergo atomic cooling) fragment to form a starburst lasting for $\sim 10^7$ years, and the halo collapse rate is given by the Press-Schechter formalism (Sasaki 1994):

$$\frac{d\dot{N}^{form}}{dM}(M, z) = \frac{1}{D} \frac{dD}{dt} \frac{dn_{PS}}{dM}(M, z) \frac{\delta_c^2}{\sigma^2(M) D^2} \quad (5)$$

where $D(z)$ is the growth factor, and $\delta_c = 1.7$ is the threshold above which mass fluctuations collapse. In this case the star formation rate is given by:

$$\dot{\Omega}_*(z) = \frac{1}{\rho_c(z)} \frac{1}{t_o} \frac{\Omega_b}{\Omega_m} f_{star} \int_{t(z)-t_o}^{t(z)} dt \int_{M(T_{vir}=10^4 K, z)}^\infty dM \frac{d\dot{N}^{form}}{dM}(M, z) M \quad (6)$$

An approximate fit to the comoving star formation rate in the interval $3 < z < 10$ can be given by $\dot{\rho}_* = \exp(a_0 + a_1 z + a_2 z^2) \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} h^3$, where $a_0 = -0.841, a_1 = 0.395, a_2 = -0.0295$. The comoving emissivity is:

$$\epsilon_\nu(t) = \rho_c \int_0^t dt' F_\nu(t - t') \dot{\Omega}_*(t') \quad (7)$$

where $F_\nu(\Delta t)$ is the stellar population spectrum, defined as the power radiated per unit frequency per unit initial mass by a generation of stars with age Δt . I obtain this spectrum from the Bruzual & Charlot (1993) code for a $Z = 10^{-2} Z_\odot$ population (i.e., extremely low metallicity), assuming a Salpeter IMF with lower and upper mass cutoffs at 0.1 and 100 M_\odot , and only computing the emissivity redward of the Lyman break. I ignore the effects of dust extinction, which should be negligible at these high redshifts when the metallicities are very low.

3.1. Recombination radiation

Is the number density of recombination line photons such as Ly α sufficiently high to cause significant pair production opacity? It has been emphasized (e.g., Loeb & Rybicki 1999) that apart from possible dust attenuation, Ly α photons are not absorbed by the IGM but resonantly scattered until they redshift out of resonance. Indeed, the Ly α radiation intensity has been predicted to be particularly strong prior to the epoch of reionization (Haiman, Rees & Loeb 1997, Baltz, Gnedin & Silk 1998). This is because the optical depth in the Lyman series is very high, and all the Lyman series lines except Ly α are absorbed immediately and redistributed. Thus, the Ly α and Balmer lines are considerably brighter because they receive the energy of the Lyman series. This has spawned suggestions of detecting the epoch of reionization by a sharp drop in intensity at the

rest-frame Ly α wavelength (Baltz, Gnedin & Silk 1998, Shaver et al 1999). In particular, Baltz, Gnedin & Silk (1998) find that Ly α is about 3 times brighter and H α is about 30 times brighter immediately prior to the reionization redshift.

If this is indeed the case, Ly α photons might contribute significantly to the pair production opacity. Let us define $f_{jump} = n_{recomb, Ly\alpha} / n_{tot, Ly\alpha}$, the jump in the number density of photons longward of the Ly α wavelength. This is given by the number of photons $n_{recomb, Ly\alpha}$ injected at the Ly α wavelength, over the total number of photons $n_{tot, Ly\alpha}$, include those redshifting into resonance. Most studies calculate the number of Ly α recombination photons by summing over the IGM recombination rate in numerical simulations, by direct estimation of gas clumping in the simulations. In fact, this underestimates the number of Ly α photons produced: if the escape fraction of ionizing photons is small, most recombinations occur in the HII regions of dense halos where star formation takes place, and the primary source of Ly α photons are the ionising sources themselves. If each ionizing photon is converted into a Ly α photon (plus lower energy photons) at the source, then $\dot{n}_{Ly\alpha} \approx \dot{n}_{ion}(1 - f_{esc})$, where f_{esc} is the average escape fraction of ionizing photons from a source. Thus, inserting $\epsilon(\nu, z) = E_{Ly\alpha} \dot{n}_{ion}(1 - f_{esc}) \delta(\nu - \nu_{Ly\alpha})$ into equation (4), I obtain for $\nu < \nu_{Ly\alpha}$, the solution

$$J_{\nu}^{Ly\alpha}(z) = \frac{1}{4\pi} \frac{c}{H_o} h_P \left(\frac{\nu}{\nu_{Ly\alpha}} \right)^{-3} \frac{1}{(\Omega_m(1+z_s)^3 + \Omega_{\Lambda})^{1/2}} \dot{n}_{ion}(z_L)(1 - f_{esc}) \quad (8)$$

where $\dot{n}_{ion}(z)$ is the production rate of ionizing photons in proper coordinates, *prior* to attenuation by the ionizing photon escape fraction. This is a lower bound on $J_{\nu}^{Ly\alpha}(z)$ since it does not include the conversion of photons trapped in higher order Lyman resonances to Ly α photons. I find that for the adopted stellar spectra, in which the Lyman edge is typically $f_{break} \sim 5$, then typically $f_{jump} \sim 1$, which implies that Ly α photons are comparable to UV continuum photons as a source of opacity. The jump factor f_{jump} may easily be understood as the ratio of the total number of Lyman alpha photons produced (or, the total number of ionizing photons produced) against the total number of photons in the 10.2 – 13.6eV range. If the break at the Lyman edge is reduced, then f_{jump} is increased and Ly α photons are more important in contributing to the pair-production opacity. In particular, for a power law spectrum with no discontinuity at the Lyman edge (e.g. as for quasars), Ly α photons are the dominant source of opacity. Ly α photons are also the dominant source of opacity in scenarios where the universe is reionized by zero metallicity stars. The higher effective temperature of these Pop III stars imply that their spectrum is much harder, and significantly fewer photons are emitted longward of the Lyman break (Tumlinson & Shull 2000).

Ly α photons could thus an important source of pair production opacity provided the escape fraction is small, i.e. $(1 - f_{esc}) \approx 1$, and dust attenuation while the Ly α photons resonantly scatter in the IGM is unimportant. If Ly α photons are the dominant source of pair production opacity, this would be extremely interesting, as it would provide a indirect census of the ionizing photon emissivity, prior to attenuation within the host sources. This could prove to be a good measure of the comoving star formation rate. One way to check if this is the case would be to directly image sources in NGST in rest frame UV longward of Ly α (sufficiently far away from the Ly α damping

wing), as well as in rest frame Balmer line emission (which should also be directly proportional to the production rate of ionizing photons, $\dot{n}_{H\alpha} \propto \dot{n}_{Ly\alpha} \propto \dot{n}_{ion}(1 - f_{esc})$). This will give a sense as to whether Ly α or UV continuum photons are a greater source of opacity, provided the trend observed in bright sources extrapolates down to lower luminosities.

3.2. Results

Fig 2 shows the predicted attenuation factor as a function of observed photon energy, for grazars at redshifts $z_s = 3, 6, 10$, for both high ($f_{star} = 17\%$) and low ($f_{star} = 1.7\%$) star formation efficiencies. There are several important features to note. Firstly, the shape of the attenuation curve for Ly α is similar to that for UV continuum photons. It is not possible to immediately distinguish between scenarios where Ly α photons and UV continuum photons are the dominant source of opacity. Secondly, for lower star formation efficiencies, attenuation both sets in at only at higher energies and the attenuation curve is significantly shallower (i.e., it reaches full attenuation after a much longer energy interval). This is easy to understand. Gamma-ray photons of higher energy have both a longer path-length to travel before they redshift to $E < E_{th}$, and a higher number density $n(\epsilon_{th} < \epsilon < \epsilon_L)$ of photons to pair produce against, since $\epsilon_{th} \sim (m_e c^2)^2/E$ is lower. Thus, if the overall number density of UV photons is lower, one must go to higher energies to achieve the same attenuation. In Figure 3, I show the relative contribution of different rest-frame target photon energies and redshift intervals for gamma-ray photons with $\tau(E_o, z_s) = 1$, for a variety of source redshifts. The shape of these curves is largely dependent on the overall number density of target UV photons. For a lower SFR, the energy E_o at which $\tau(E_o, z_s) = 1$ increases, and the target photon interval and redshift interval contributing to the resultant opacity broadens. Note that most of the opacity comes from redshifts comparable to that of the source. Also, the opacity arises from a fairly narrow target photon energy interval $\sim 3 - 13.6\text{eV}$; this varies weakly with source redshift. Thus the results do not depend strongly on the assumed spectral slope of the UV sources. I also obtained by direct computation the contribution to the opacity due to ionizing photons shortward of the Lyman edge. Depending on one's assumptions for $f_{esc}, f_{break}, f_{opacity}$, it is smaller by 2–4 orders of magnitude, and is completely negligible.

An important technique for isolating the contribution of high-redshift radiation fields would be to use measurements of *differential* absorption between blazars at different redshift. Consider two blazars with at redshifts z_1 and z_2 , with $z_2 > z_1$. At a given observed energy E_o , photons from each blazar will encounter identical optical depths for $z < z_1$. Thus, any additional opacity seem in the spectrum of the blazar at z_2 must arise from the redshift interval $z_1 < z < z_2$ alone, $\Delta\tau(E_o) = \int_{z_1}^{z_2} dz \frac{dl}{dz} \int_{-1}^1 d(\cos\theta) (1 - \cos\theta) \int_{\epsilon_{th}}^{\infty} d\epsilon n(\epsilon, z) \sigma(E, \epsilon, \theta)$. Note that this identification is independent of any uncertainties in the spectral slope or redshift evolution of the UV background. As argued above, radiation field intensity fluctuations are unimportant since the pair-production opacity arises on scales of order a Hubble length. Thus, in Figure (2), any difference between the $z_s = 3, 6, 10$ curves is solely due to radiation fields between $3 < z < 6$ and $6 < z < 10$; if star

formation ceases for $z > 3$, the curves would lie on top of one another. If there is little difference between two absorption curves from sources at z_1 and z_2 , one can get an upper bound on the UV emissivity in the range $z_1 < z < z_2$; likewise, if two curves are so widely separated that meaningful measurements of $\Delta\tau(E_o)$ cannot be obtained (in particular, if absorption saturates in one of the curves), one can get a lower bound on the UV emissivity in the range $z_1 < z < z_2$. In Figure (4), I show how the attenuation at a fixed observed photon energy E_o is expected to rise with redshift, due to the opacity provided by high redshift UV fields. For lower star formation efficiency, the attenuation rises more slowly; if there is no star formation at high redshift the curve would be flat. In Figure (5) I show how the energy E_o for which $\tau(E_o, z_s) = 1$ is expected to fall with increasing redshift; due to the increased opacity provided by high redshift photons, attenuation sets in at lower energies. Again, if there were no star formation at high redshift, this curve would show no evolution.

In fact, differential absorption measurements provide a powerful cross-check on the technique: if $\tau(E_o, z_2) < \tau(E_o, z_1)$, then the assumed unabsorbed blazar spectrum must be evolving with redshift, due to a change in internal absorption, or underlying spectral index. Note that if star formation rates are high, the attenuation occurs rapidly over a small energy interval, and uncertainties due to the extrapolation from the unabsorption portion of the spectrum is small; for lower star formation rates the attenuation occurs over a larger energy interval, and uncertainties due to extrapolation are greater.

4. Conclusions

In this paper, I have suggested that if blazars can be detected at high redshift, detection of gamma-ray absorption due to pair production against high-redshift UV photons will provide a valuable probe of high-redshift UV radiation fields. This is because the sharp Lyman edge in the intergalactic radiation fields implies that gamma-ray photons have only a limited redshift interval in which to pair-produce. As they redshift to lower energies, they require photons with $\epsilon > 13.6\text{eV}$ to pair-produce, so the universe becomes optically thin. The shape of the attenuation curve is primarily sensitive to the overall number density of photons longward of the Lyman edge at high redshifts: the higher this number density, the lower the gamma-ray photon energy at which pair-production opacity sets in. This makes it a useful test of the overall level of star formation and ambient UV radiation fields present at high redshift. $\text{Ly}\alpha$ photons provide an important contribution to this pair production opacity, and indeed may be the dominant source of opacity if sources with a relatively lower fluxes longward of the Lyman edge (such as quasars or low metallicity stars) are abundant. Finally, measurements of differential absorption between blazars at the same observed energies will allow us to cleanly isolate the increase in opacity due to radiation fields at high redshift.

There are two large uncertainties. The first is whether GLAST will be able to see high-redshift blazars at all. However, in the unified model of AGN, the scarcity of ultra-luminous blazars is a geometrical effect (due to relativistic beaming) rather than a requirement of extremely large black

hole masses. In fact, the luminosity boost provided by beaming reduces the black hole mass by several orders of magnitude below that demanded by the Eddington limit. So it is at least plausible that high redshift blazars will be detectable. The second uncertainty is whether absorption seen in a blazar will be internal, rather than due to pair production against photons in the IGM. However, at GeV energies we have some physical understanding of the observed EGRET spectra (e.g., Ghisellini et al 1998); opacity to gamma-ray photons due to internal radiation fields can be constrained by time variability arguments and other constraints. Furthermore, GLAST should assemble an extremely large catalog ($>$ few thousand) of low redshift blazars, whose spectra can be studied in detail (and the contribution to opacity due to low redshift star formation can be quantified by other means); provided blazar properties do not evolve too strongly with redshift, we should have a firm handle on the intrinsic unabsorbed blazar spectrum.

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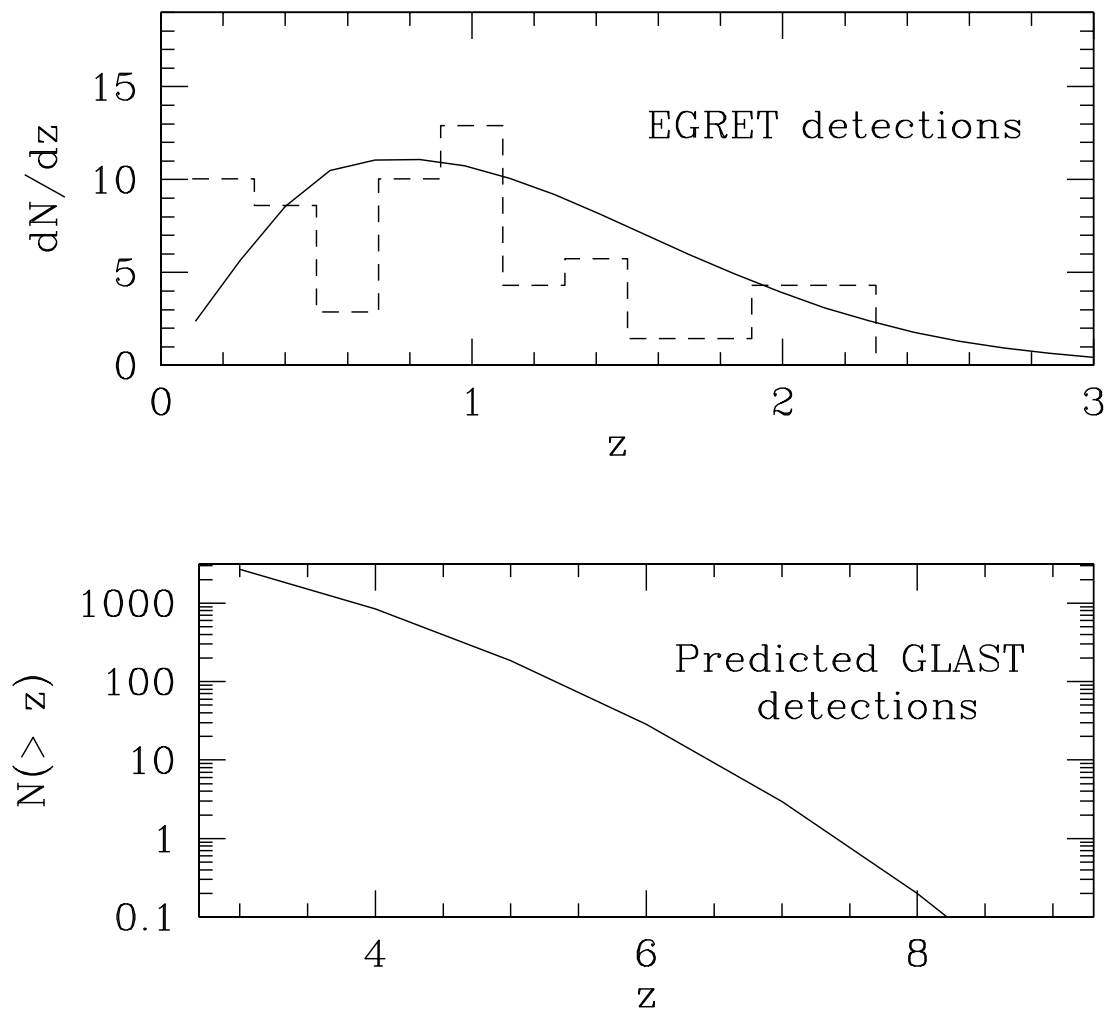


Fig. 1.— Top panel: Best fit model(solid line) for blazar detection over the entire sky with EGRET detection threshold $S(E > 100\text{MeV}) = 2 \times 10^{-7} \text{ photons s}^{-1} \text{ cm}^{-2}$, against actual number of sources detected (dotted line). The model assumes $\gamma = 6$ and $L_{\gamma,13}^{\text{intrinsic}} = 3.2 \times 10^{-2} L_{B,13}^{0.9}$. Bottom panel: predicted number of blazar detections with GLAST detection threshold $S(E > 100\text{MeV}) = 2 \times 10^{-9} \text{ photons s}^{-1} \text{ cm}^{-2}$ as a function of redshift.

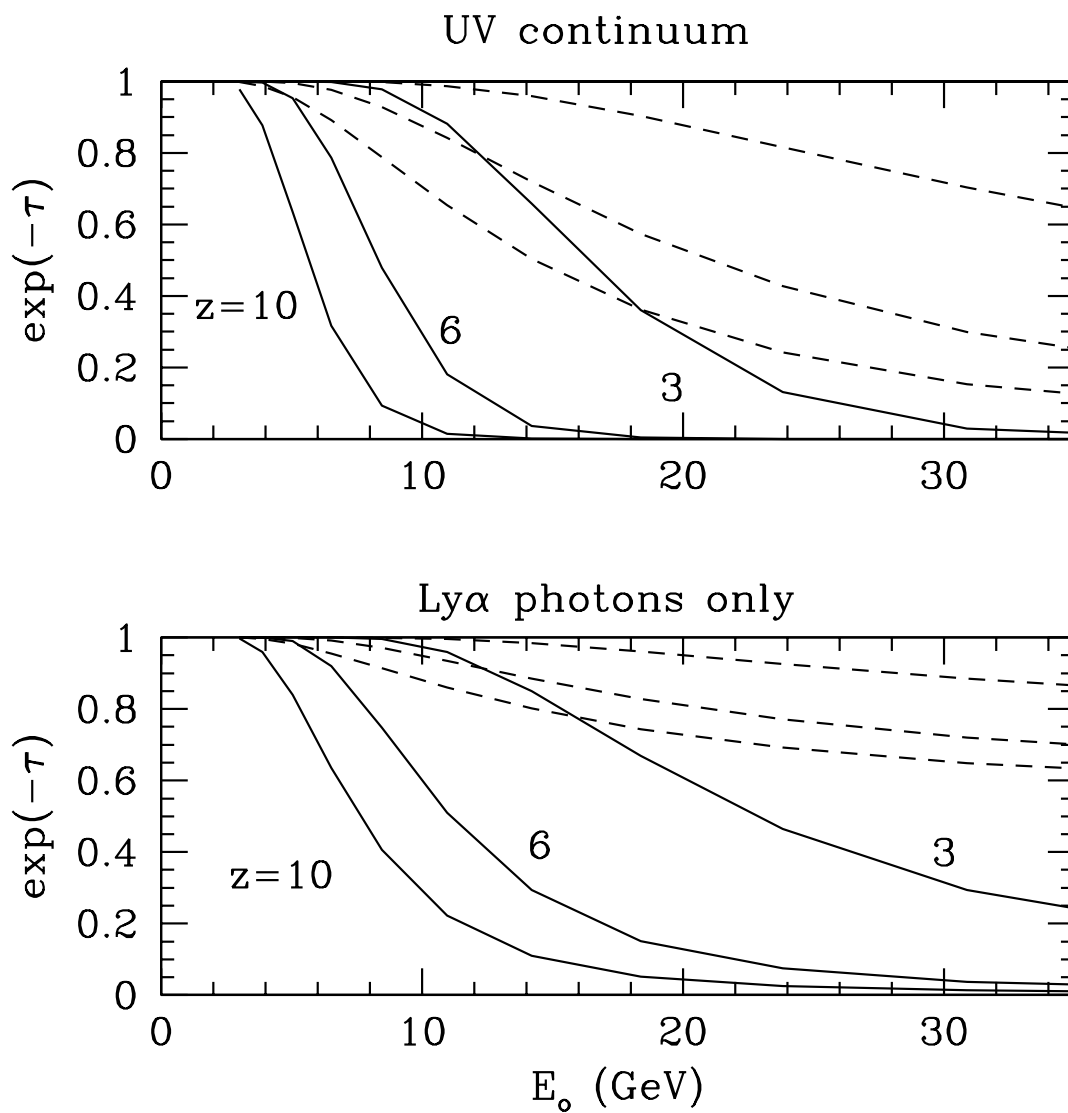


Fig. 2.— The predicted attenuation factor as a function of observed photon energy E_o for UV continuum opacity (top panel) and Ly α photon opacity only, for source redshifts $z_s = 3, 6, 10$. The solid lines are for a high star formation efficiency ($f_{star} = 17\%$), and dashed lines are for a low star formation efficiency ($f_{star} = 1.7\%$).

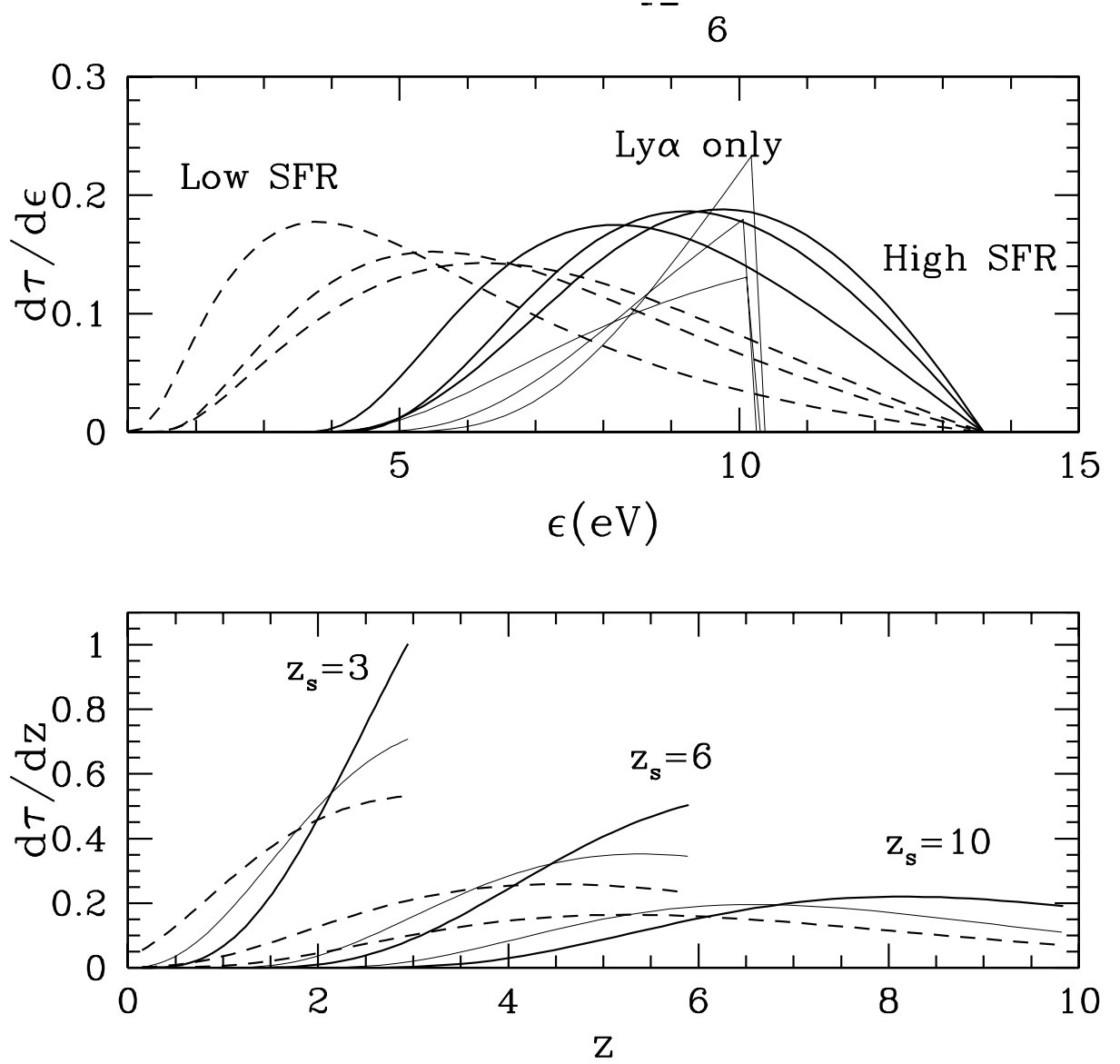


Fig. 3.— The contribution of rest-frame target photon energy interval (top panel) and redshift interval (bottom panel) to the opacity, all for gamma-ray photons for which $\tau(E_o, z_s) = 1$. Figures are for 3 different source redshifts ($z_s = 3, 6, 10$) and 3 different UV emissivity scenarios: high SFR ($f_{star} = 17\%$, dark solid line), low SFR ($f_{star} = 1.7\%$, dashed line), Ly α photon opacity only (assuming high SFR, thin solid line). Note that contribution of different energy intervals evolves only weakly with source redshift ($z_s = 3, 6, 10$ from right to left in top figure). As the number density of target photons decreases (low SFR), the distribution of energy and redshift interval contributions broadens.

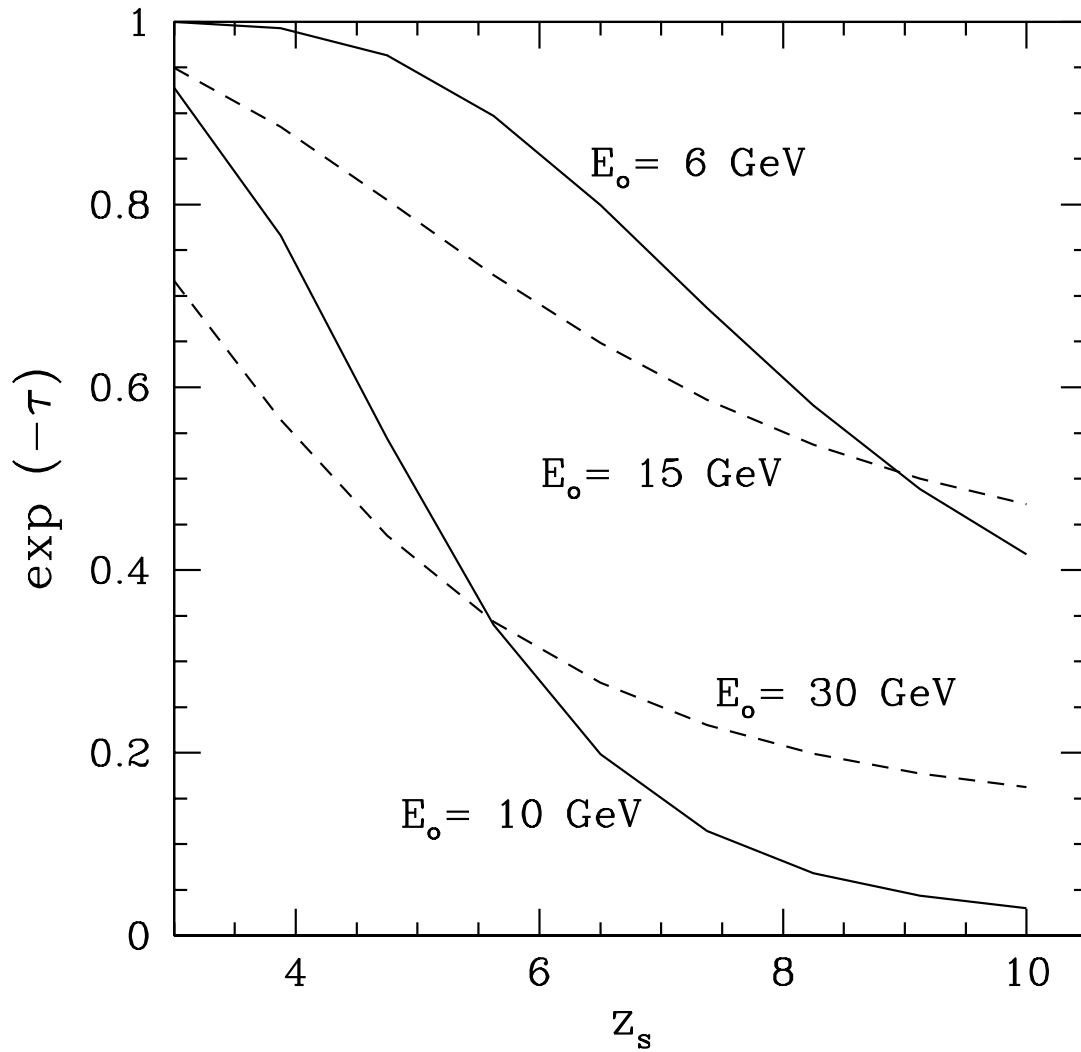


Fig. 4.— The attenuation factor as a function of blazar redshift for a given observed photon energy. Solid curves are for the high star formation efficiency case, dashed curves are for the low star formation efficiency case. Any increase in the attenuation between z_1 and z_2 is solely due to UV radiation in the range $z_1 < z < z_2$. Note that if the star formation efficiency is low, the degree of attenuation changes much more slowly with redshift.

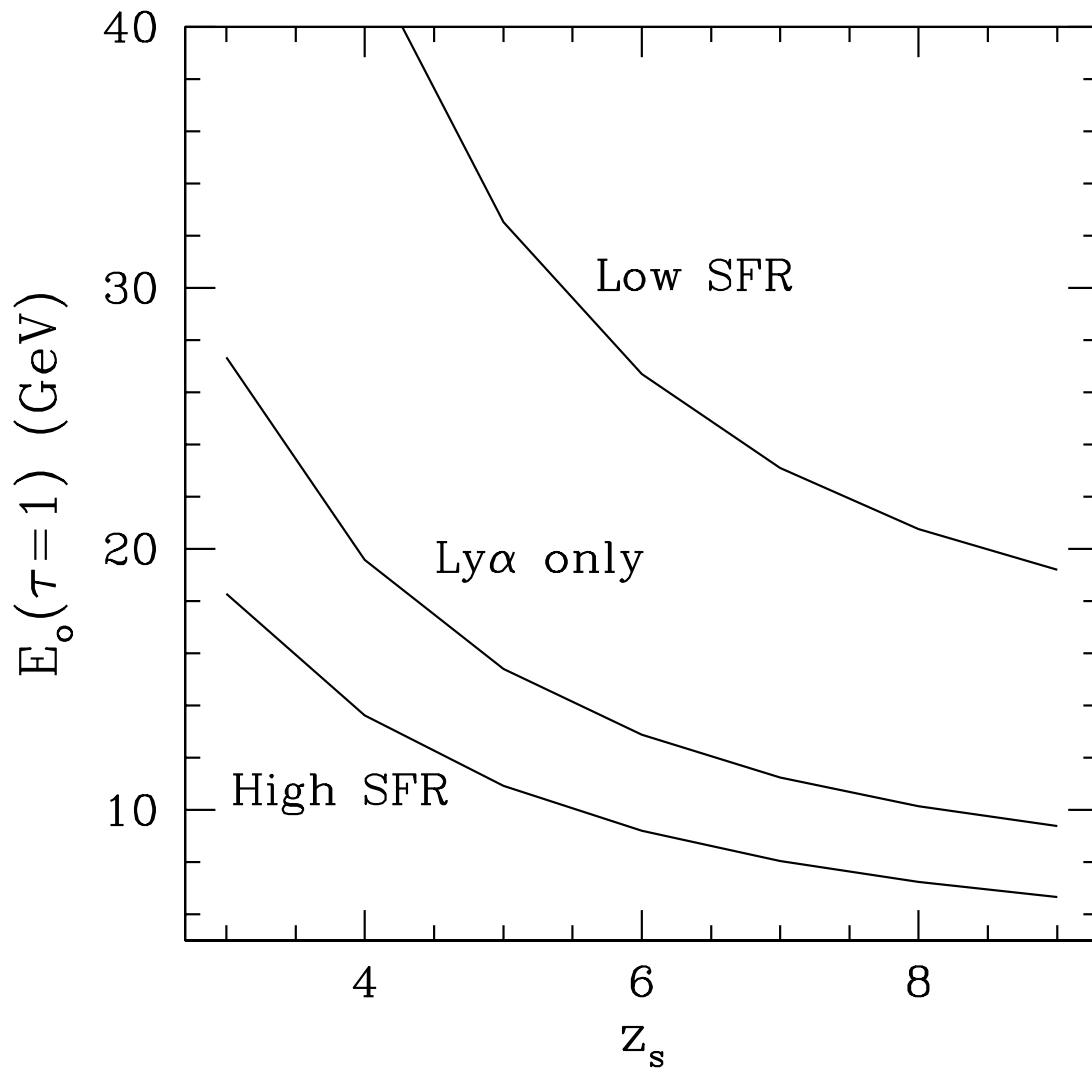


Fig. 5.— The variation of the observed energy E_o at which $\tau = 1$ with source redshift, for a high star formation efficiency ($f_{star} = 17\%$), a low star formation efficiency ($f_{star} = 1.7\%$), and a high star formation efficiency model where Ly α photons provide the main source of opacity. Note how the curve flattens at high redshift due to the reduced opacities at high redshift. If the pair production opacity at high redshift is negligible, the curve would be completely flat.